



Energy Reconstruction and Calibration of the MicroBooNE LArTPC

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On behalf of the MicroBooNE Collaboration

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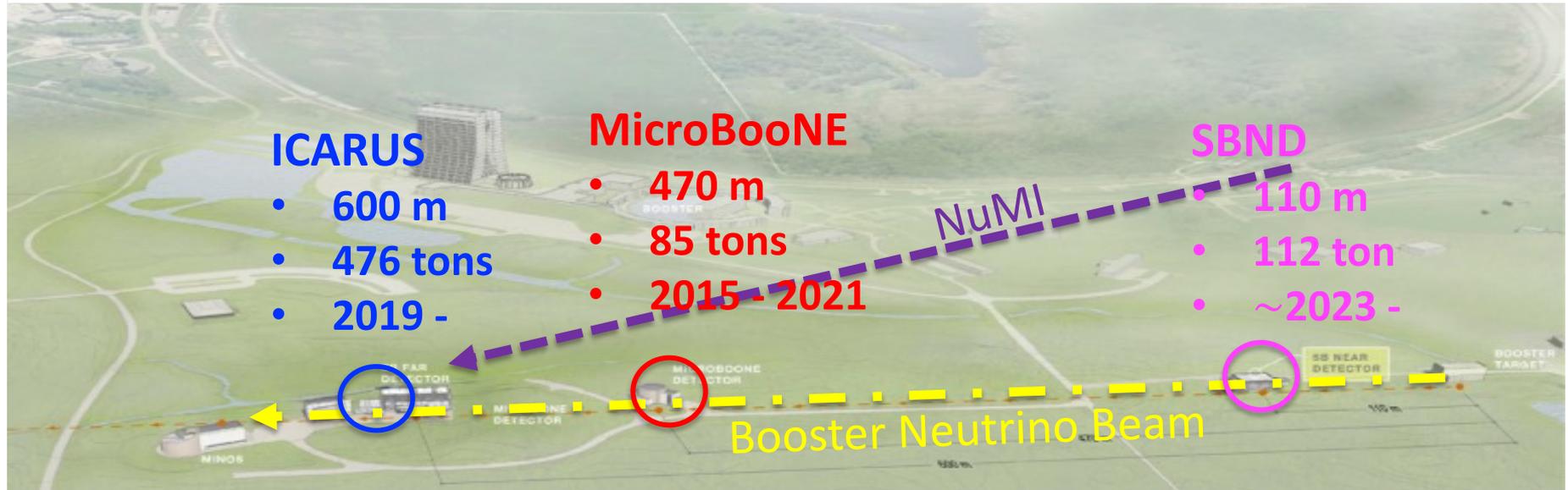
MicroBooNE Experiment

Part of the Fermilab Short Baseline Neutrino (SBN) program:

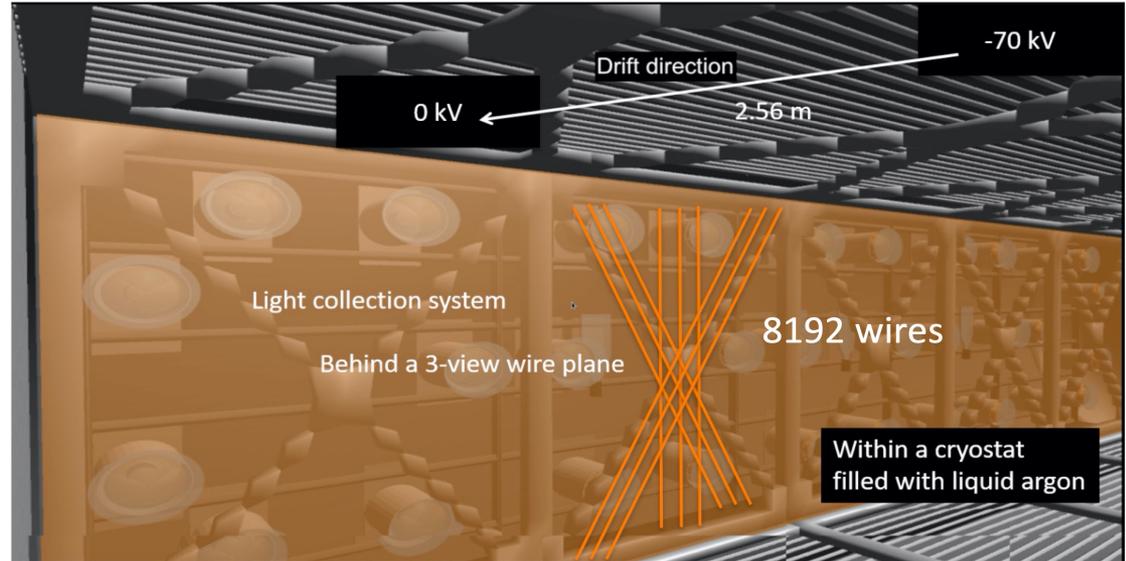
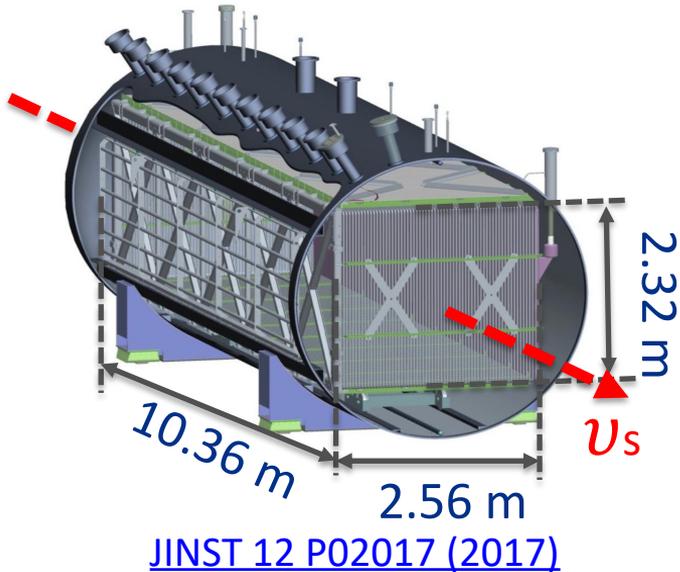
- liquid argon time projection chamber (LArTPC) detector

Major goals:

- Investigate MiniBooNE's low energy excess
- Measure the neutrino-argon cross sections
- Develop LArTPC techniques



MicroBooNE Detector



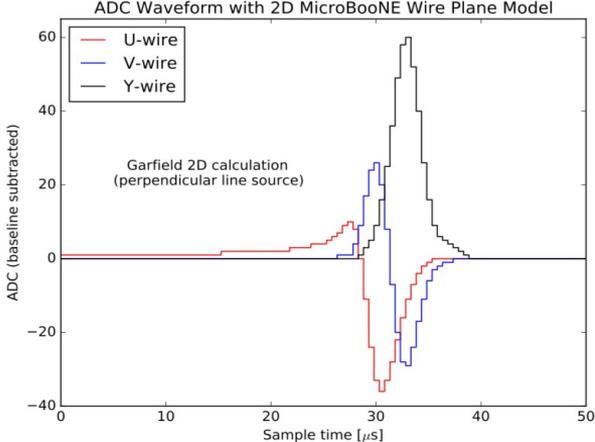
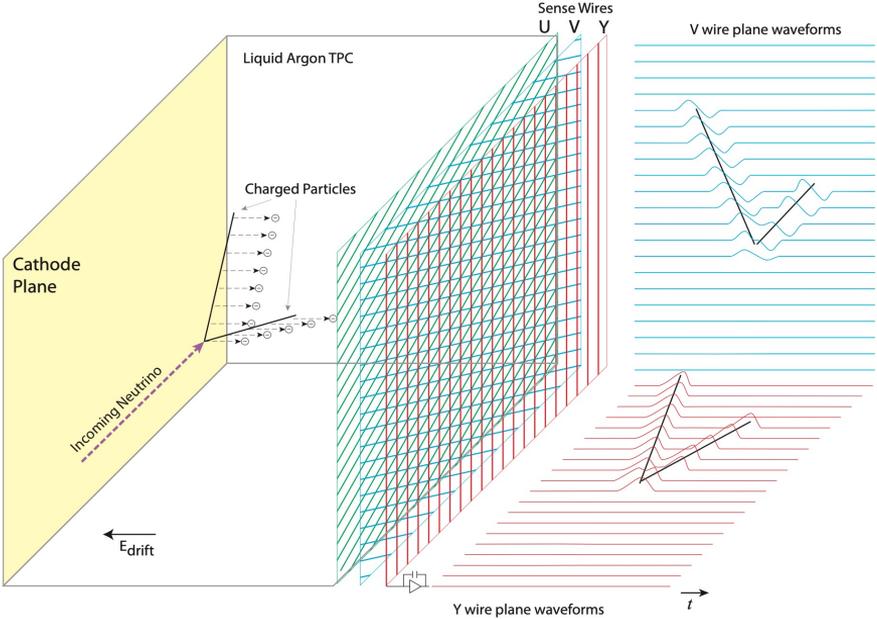
Three wire planes for charge collection:

- 3 mm plane-to-plane spacing with a 3 mm wire pitch
- Reconstruction of event and calorimetry

Light collection system

- 32 PMTs as primary subsystem
- 4 light guide paddles for R&D studies
- Mainly for trigger and event selection

MicroBooNE LArTPC



The light collection system is not shown.

LArTPC Charge Extraction

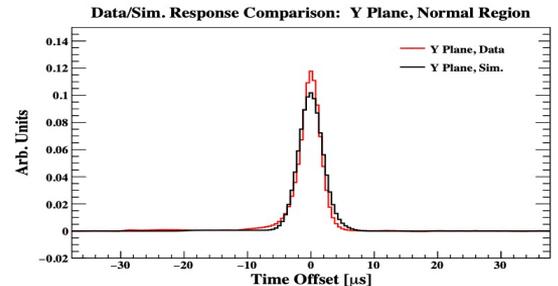
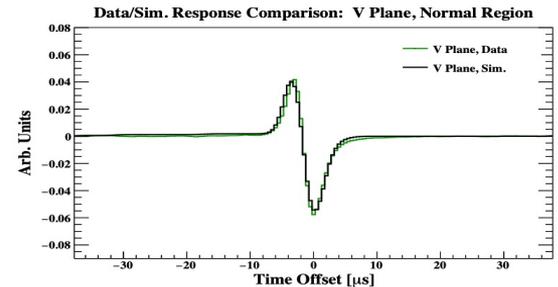
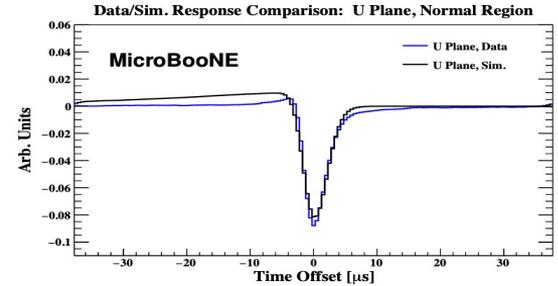
- Noise filtering: remove coherent noise, etc.
- Signal processing: use deconvolution to extract original signals
 - Deconvolution is a mathematical technique to extract the original signal $S(t)$ from the measured signal $M(t')$.

$$M(t') = \int_{-\infty}^{\infty} R(t, t') \cdot S(t) dt$$

Where $R(t, t')$ stands for detector response function

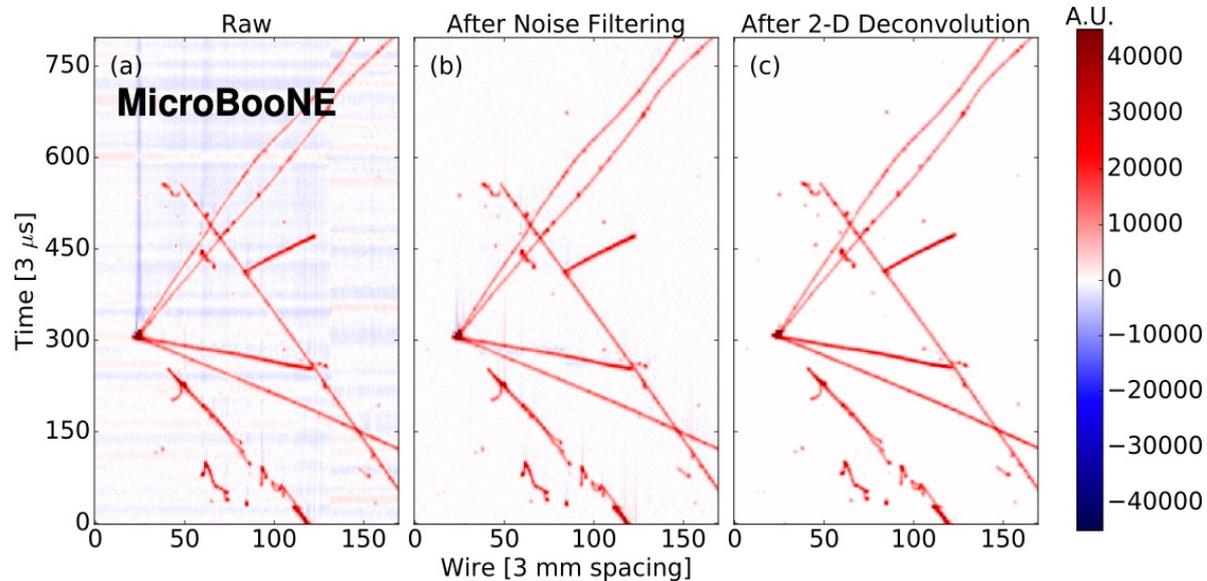
Data/simulation comparison of the full response for the different wire planes in the normal region of the MicroBooNE TPC.

[JINST 13, P07007 \(2018\)](#)



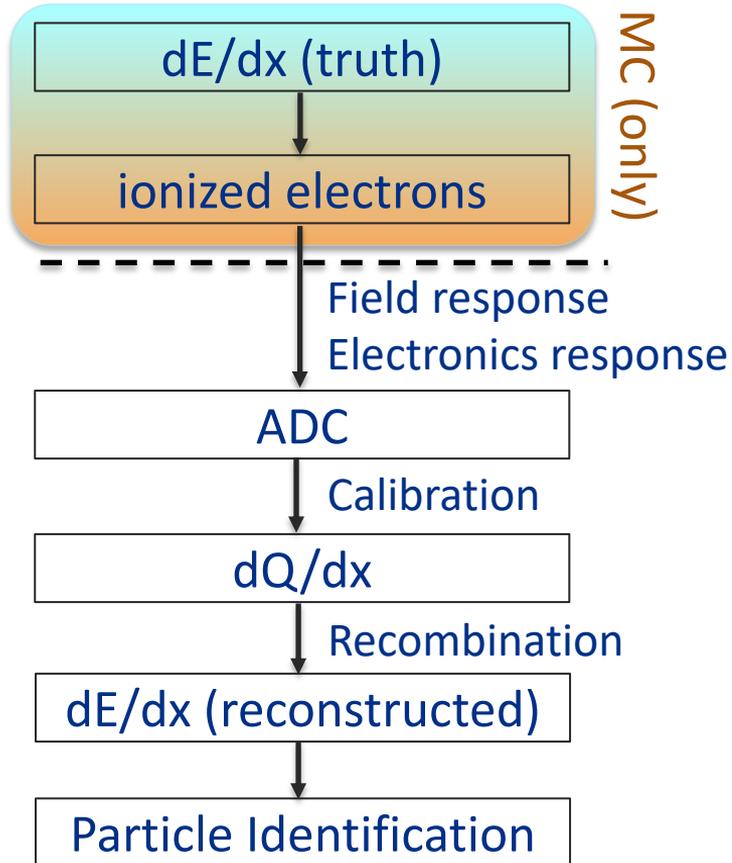
LArTPC Charge Extraction

- Noise filtering: remove coherent noise, etc.
- Signal processing: use deconvolution to extract original signals
- Output of deconvolution is a standard signal shape (i.e., a Gaussian shape) for hit (charge) reconstruction.



[JINST 13, P07007 \(2018\)](#)

LArTPC Calibration and Energy Reconstruction



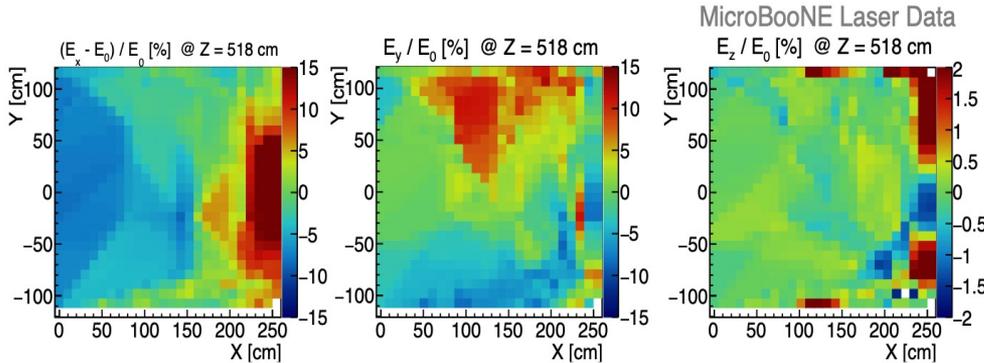
Many effects need to be calibrated:

- Space charge effects
- Variation in electronics gains
- Electron attenuation, diffusion
- Disconnected channels, TPC edge, etc.
- Temporal variation, i.e., change of run condition, temperature.
- Absolute energy scale

Space Charge Effects

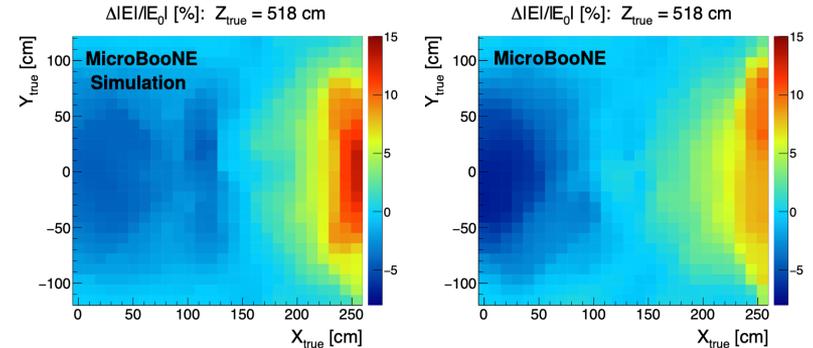
- MicroBooNE detector is on the surface (~ 20 - 30 cosmic muons per 4.8 ms readout window)
- Distortion of E field and ionization drift trajectories due to accumulation of slow-moving argon ions produced from cosmic muons impinging TPC
- Calibration on the E-field can be done by using UV laser system and the cosmic muon tracks

Relative E-field components



[JINST 15 P07010 \(2020\)](#)

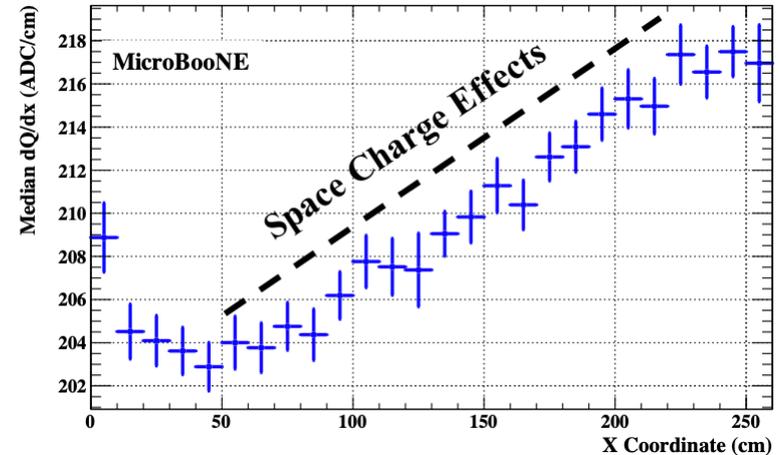
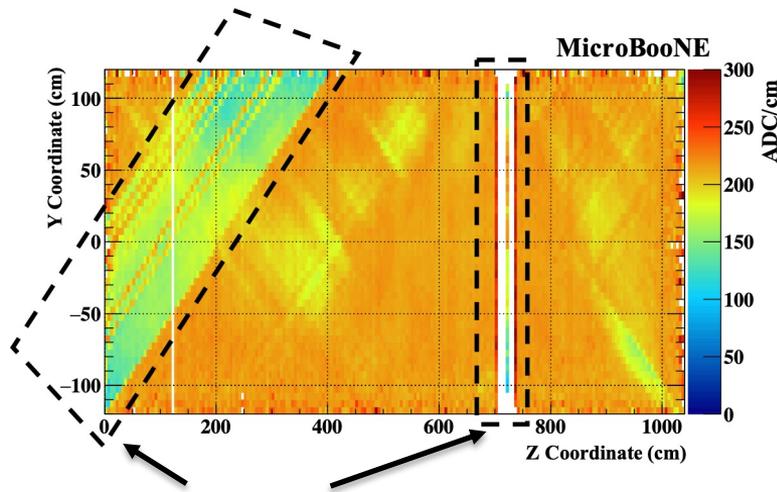
E field distortion magnitude



[JINST 15 P12037 \(2020\)](#)

Detector Uniformity Calibration–dQ/dx

- **dQ/dx calibration** (dQ/dx: ionization charge per unit length)
 - make the detector response to ionization charge uniformly throughout the detector and in time: *YZ plane, X direction, T*
 - use anode-cathode crossing cosmic muons to cover whole drift distance
- Variation of detector response (dQ/dx) in YZ plane and in the drift direction X

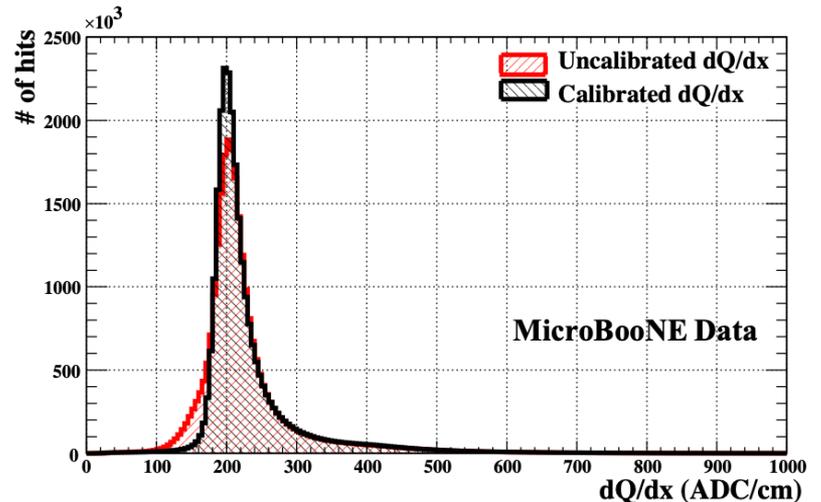
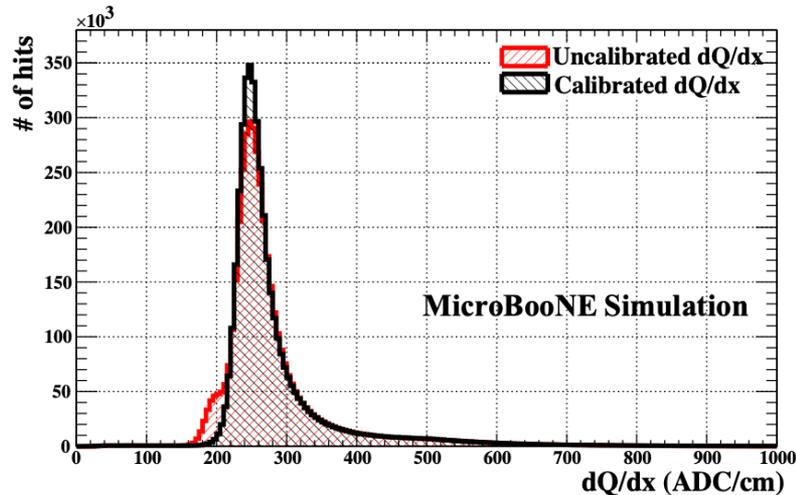


Misconfigured/cross-connected TPC channels

[JINST 15 P03022 \(2020\)](#)

Detector Uniformity Calibration–dQ/dx

- **dQ/dx calibration** (dQ/dx: ionization charge per unit length)
 - make the detector response to ionization charge uniformly throughout the detector and in time: *YZ plane, X direction, T*
 - use anode-cathode crossing cosmic muons to cover whole drift distance
- Comparisons between calibrated and uncalibrated dQ/dx for both simulation and data



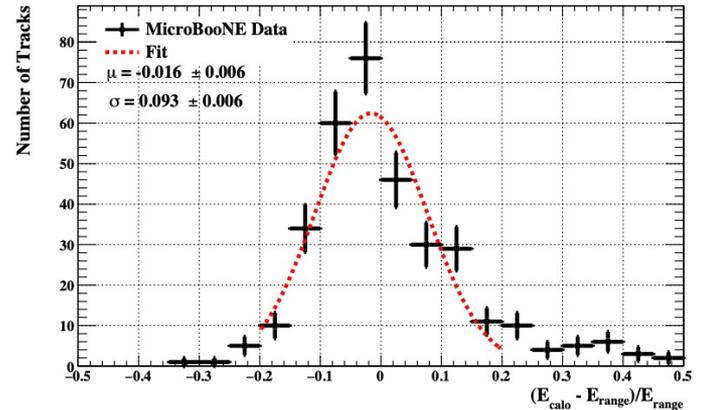
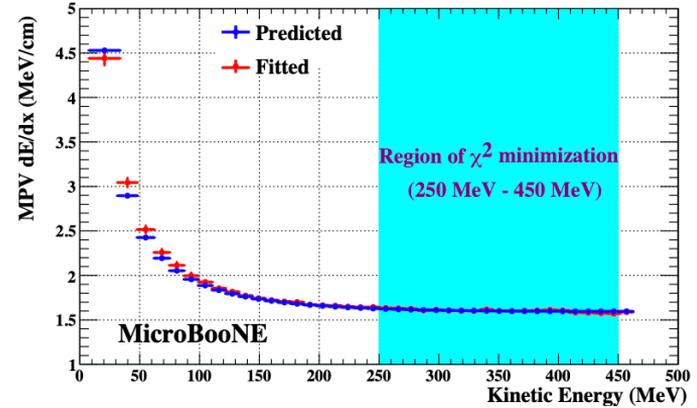
[JINST 15 P03022 \(2020\)](#)

Energy Scale Determination – dE/dx

- Determine the calibration constant C (unit: ADC/e), which translates the corrected dQ/dx (ADC/cm) to dQ/dx (e/cm).
- Stopping muons from neutrino interactions or cosmic rays are used to study the measured and predicted Most Probable dE/dx Value (MPV):

$$\left(\frac{dE}{dx}\right)_{\text{calibrated.}} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{\text{calibrated.}}}{C} \cdot \frac{\beta' W_{ion}}{\rho \xi}\right) - \alpha}{\frac{\beta'}{\rho \xi}}$$

[JINST 15 P03022 \(2020\)](#)



dQ/dx vs. dE/dx—Recombination Effects

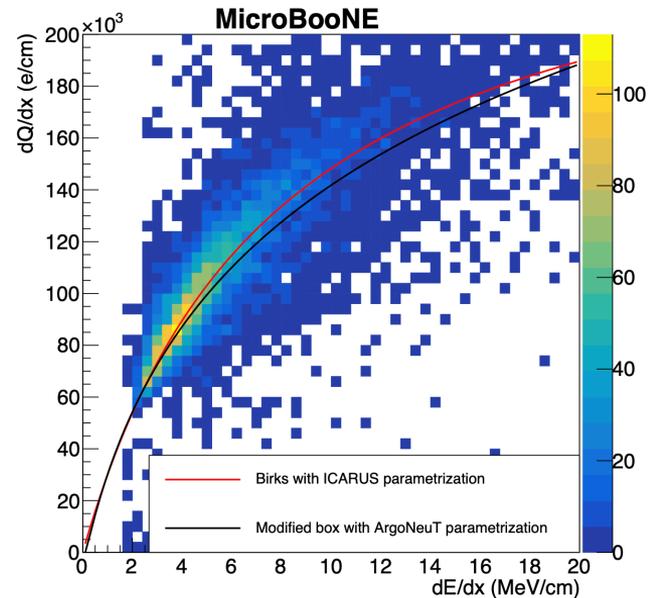
Modified box model:
$$\frac{dQ}{dx}(e/cm) = \frac{\ln\left(\frac{dE}{dx} \frac{\beta'}{\rho\mathcal{E}} + \alpha\right)}{\frac{\beta'}{\rho\mathcal{E}} W_{\text{ion}}}$$

Comparison of the measured dQ/dx vs. $(dE/dx)_{\text{range}}$ distribution with recombination models for selected proton tracks

Parameter	ArgoNeuT [JINST 8 P08005, 2013]	MicroBooNE
α	0.93 ± 0.02	0.92 ± 0.02
β' (kV/cm)(g/cm ²)/MeV	0.212 ± 0.002	0.184 ± 0.002

Birk's law:
$$\frac{dQ}{dx}(e/cm) = \frac{A_B}{W_{\text{ion}}} \left(\frac{\frac{dE}{dx}}{1 + \frac{k}{\rho\mathcal{E}} \frac{dE}{dx}} \right)$$

Parameter	ICARUS [NIM A 523 (2004) 275]	MicroBooNE
A_B	0.800 ± 0.003	0.816 ± 0.012
k (kV/cm)(g/cm ²)/MeV	0.0486 ± 0.0006	0.045 ± 0.001

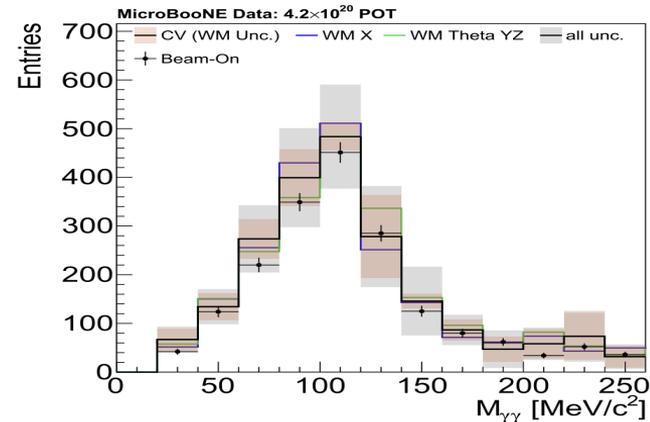
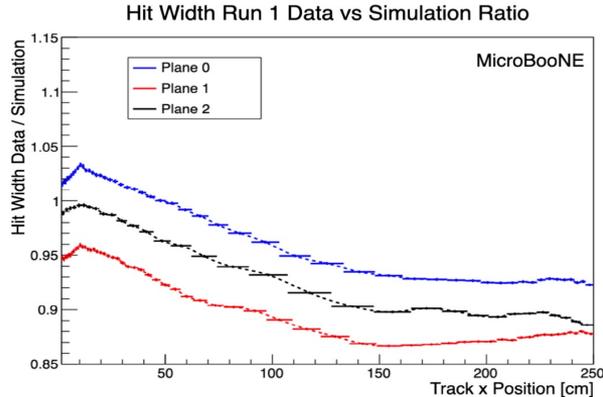


JINST 15 P03022 (2020)

Detector-Related Uncertainties

LArTPC detector systematic uncertainties are evaluated using a set of detector variations

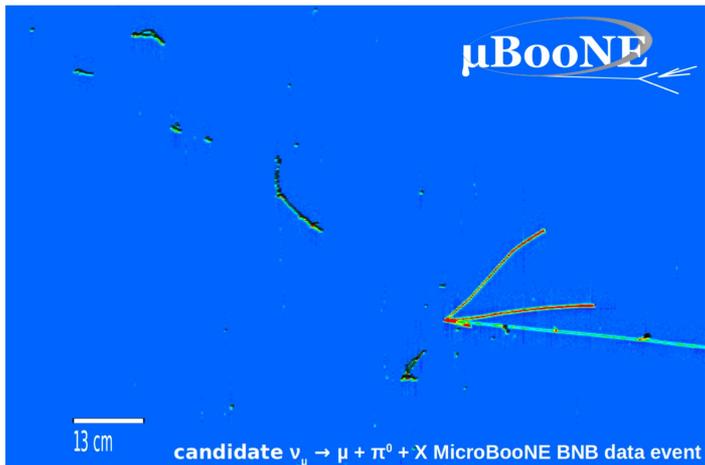
- “WireMod” variations:
 - Compare hit properties (charge and width) as a function of x , (y, z) , θ_{XZ} and θ_{YZ} between data and simulation
 - Modify the wire waveforms in simulation such that they look more like data based on the truth information of associated energy deposits
- Other TPC variations: E-field non-uniformities (SCE), recombination



[Eur. Phys. Journal C 82, 454 \(2022\)](#)

Energy Reconstruction Example — π^0 mass

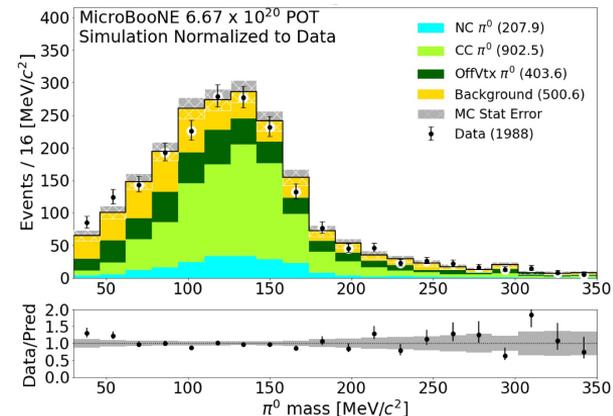
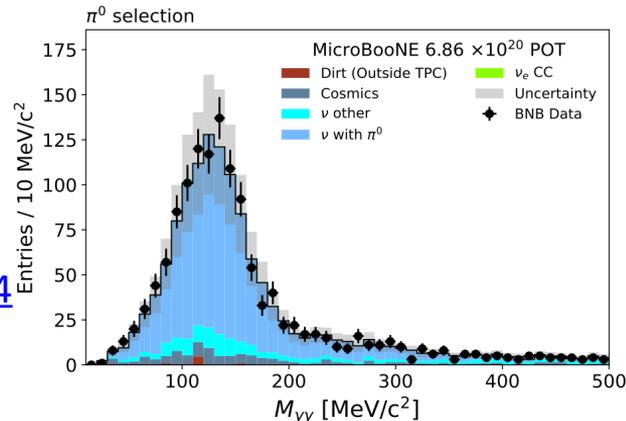
Energy reconstruction of electromagnetic showers is a crucial component in MicroBooNE, especially for the low-energy excess (LEE) analysis.



Reconstructed $M_{\gamma\gamma}$ based on [Pandora event reconstruction PRD 105 \(2022\) 11, 112004](#)

Deep-learning reconstruction: SparseSSNet for clustering shower-like hit

[JINST 16 T12017 \(2021\)](#)



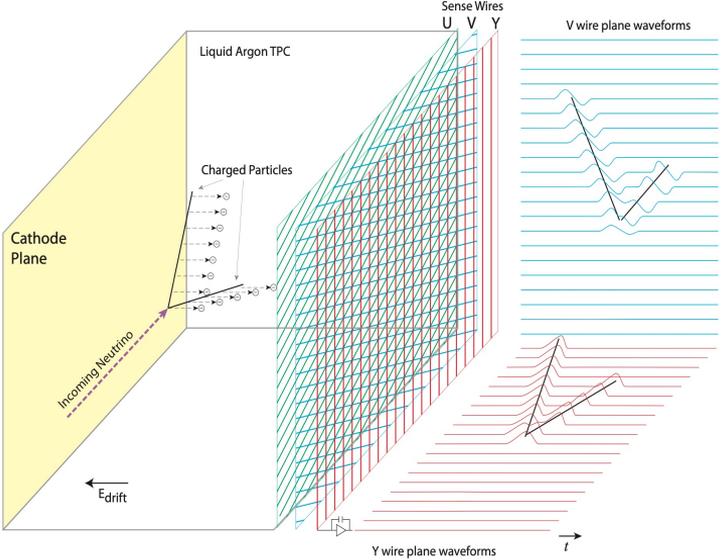
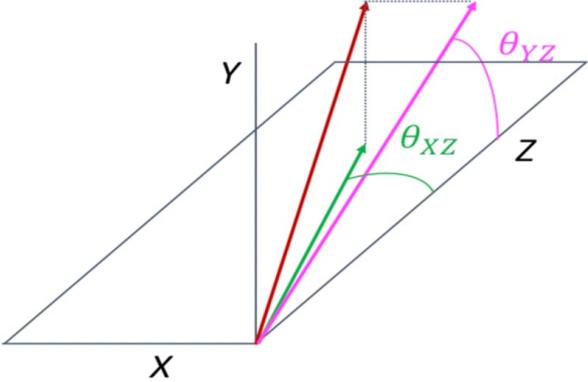
Summary

- MicroBooNE, the first operating detector in the Fermilab Short Baseline Neutrino program, has collected the world's largest dataset of neutrino-argon interactions.
- The energy reconstruction and detector calibration developed in MicroBooNE LArTPC can provide precision information for particle identification and measurements.
- The calibration procedure has been used in MicroBooNE's physics analyses, including the cross-section measurements and the recent LEE results ([Phys. Rev. Lett. 128, 241801 \(2022\)](#), [Phys. Rev. Lett. 128, 111801 \(2022\)](#)).
- The energy reconstruction and calibration strategy has been applied to other experiments (e.g., ProtoDUNE, ICARUS, SBND).

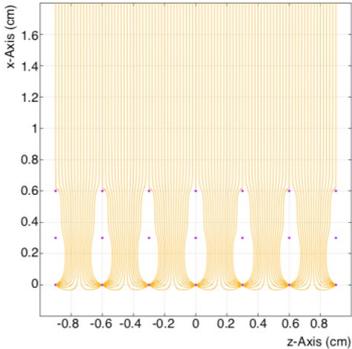
Thank you!

Backup

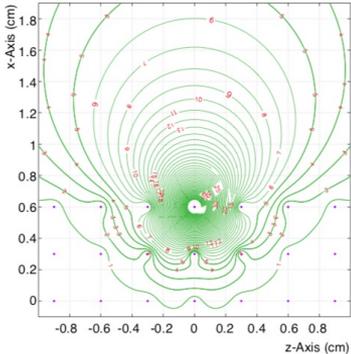
LArTPC Coordinate System



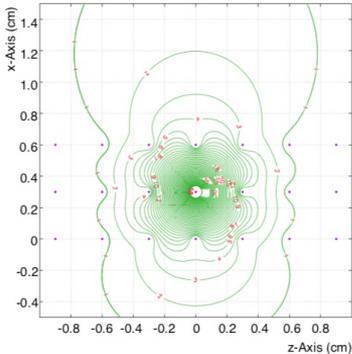
Drift Electron Path



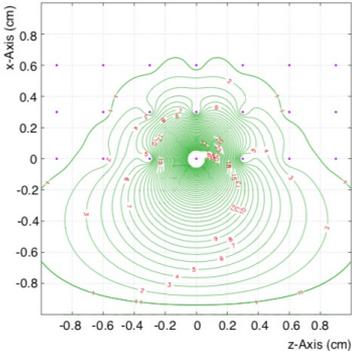
(a) Electron drift paths.



(b) Weighting potential on a U wire.



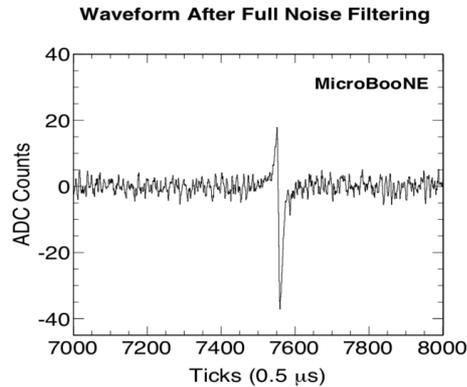
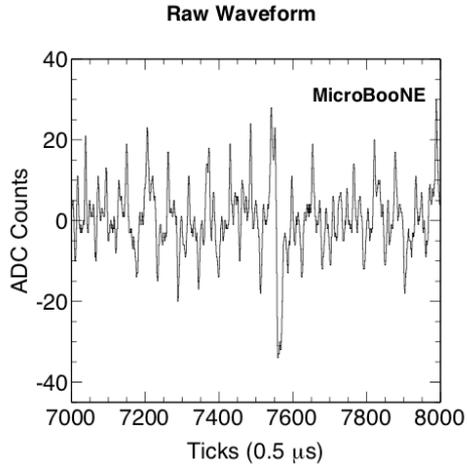
(c) Weighting potential on a V wire.



(d) Weighting potential on a Y wire.

[JINST 13, P07006 \(2018\)](#)

Noise Filtering



[JINST 12, P08003 \(2017\)](#)

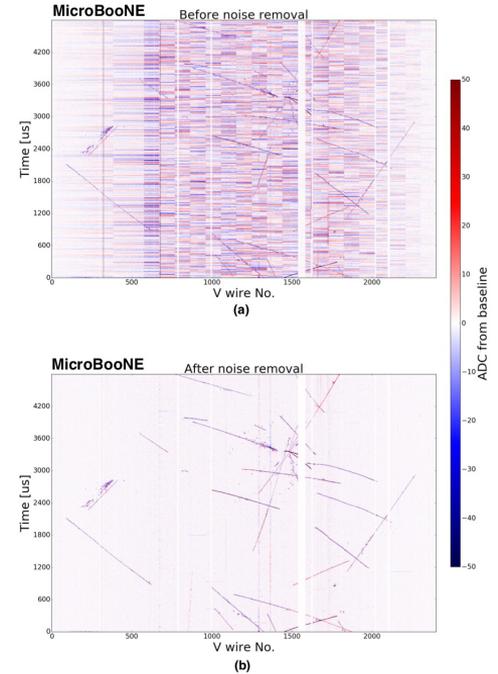
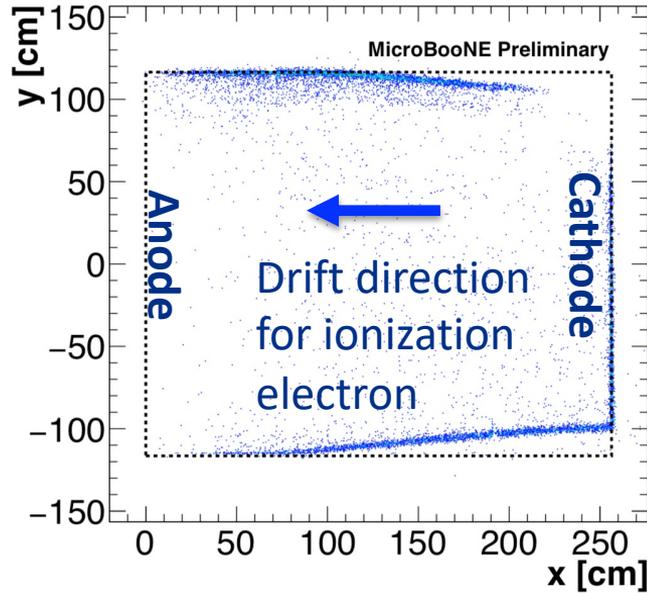


Figure 14. 2-D event display of the V plane from run 3493 event 41075 showing the raw signal (a) before and (b) after offline noise filtering. A clean event signature is recovered once all the identified noise sources are subtracted.

MicroBooNE Calibration

- Challenges for MicroBooNE LArTPC detector:
 - **Misconfigured or cross-connected TPC channels:** change gain of electronic channels, distort field between wire planes
 - **Space Charge Effects (SCE):** cosmic rays, accumulation of slow-moving Ar^+ , causing distortion the magnitude and direction of drift E field
 - **Electron attenuation:** electronegative contaminants such as H_2O and O_2 can capture some of the drifting electrons
 - **Diffusion:** drifted electrons may get smeared out
 - **Recombination:** ionization electrons may not completely liberate from their parent argon ions and recombine back to form neutral argon atoms again, causing underestimation of particle energy loss
 - **Temporal variations:** change of temperature, run conditions...
 - ...
- We want to measure the charge and position of ionization signal precisely and improve both the measurement of total deposited energy and particle identification (PID).

Space Charge Effects



Start/end points of reconstructed cosmic muon tracks tagged by an external muon counter in the x-y plane for off-beam (cosmic) events.

[JINST 15 P12037 \(2020\)](#)

Space Charge Effects

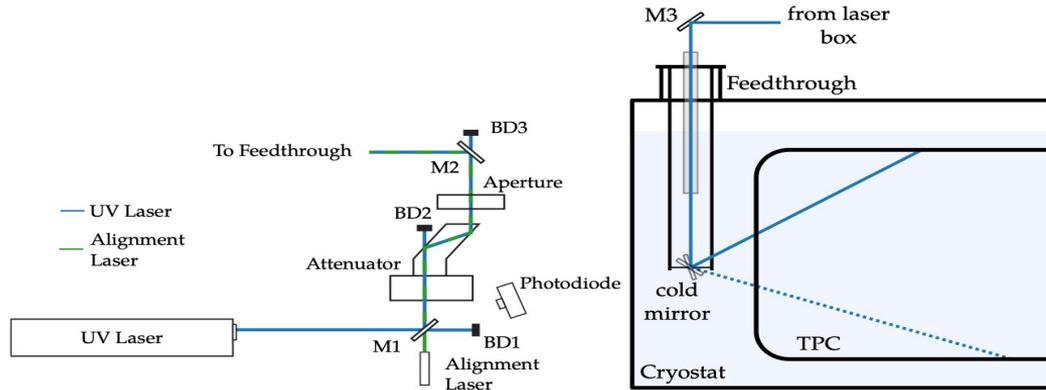


Figure 1. The laser system of MicroBooNE; the upstream and downstream laser sub-systems have the same layout. *Left:* The optical path of the laser beam before entering the cryostat. The 266 nm laser beam is aligned by two mirrors (M1 and M2), and directed towards the feedthrough. An attenuator for beam energy control and an aperture for beam size control are placed in between the two mirrors M1 and M2. A photodiode provides a trigger for the readout. *Right:* Schematic of the laser feedthrough in the cryostat. The UV laser beam reflects at the dichroic mirror M3 and then enters an evacuated quartz tube which serves as light guide to avoid defocusing of the laser beam at the LAr surface. The cold mirror can rotate horizontally together with the feedthrough assembly. A movable rod extending to a cogwheel allows the cold mirror to rotate vertically. The supporting structure of the cold mirror is mounted to the feedthrough flange.

[JINST 15 P07010 \(2020\)](#)

dQ/dx

➤ $\left(\frac{dQ}{dx}\right)_{uncorr.} \rightarrow YZ_{corr.} \rightarrow DriftDirection_{corr.} \rightarrow Time_{corr.} \rightarrow \left(\frac{dQ}{dx}\right)_{corr.}$

- Consists of 3 steps:

1. YZ plane correction: remove effects from SCE, misconfigured or cross-connected TPC channels and transverse diffusion
2. Drift direction correction: remove effects coming from electron attenuation, SCE and longitudinal diffusion
3. Time correction: remove any temporal variations in detector response (for data only, MC does not have time dependence)

➤ $\left(\frac{dQ}{dx}\right)_{uncorr.} \rightarrow YZ_{corr.} \rightarrow Lifetime_{corr.} \rightarrow \left(\frac{dQ}{dx}\right)_{corr.}$

- Consists of 2 steps:

1. YZ plane correction: same as above
2. Lifetime correction:
 - remove effects coming from electron attenuation, SCE and longitudinal diffusion, temporal variations
 - $Q = Q' \cdot e^{-\left(\frac{t}{\tau}\right)}$ (t: drift time; τ : electron lifetime, determined by purity or TPC (laser system, muon count system)

$$\left(\frac{dE}{dx}\right)_{corr.} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{corr.} \cdot \frac{\beta' W_{ion}}{\rho \xi}}{C}\right) - \alpha}{\frac{\beta'}{\rho \xi}}$$

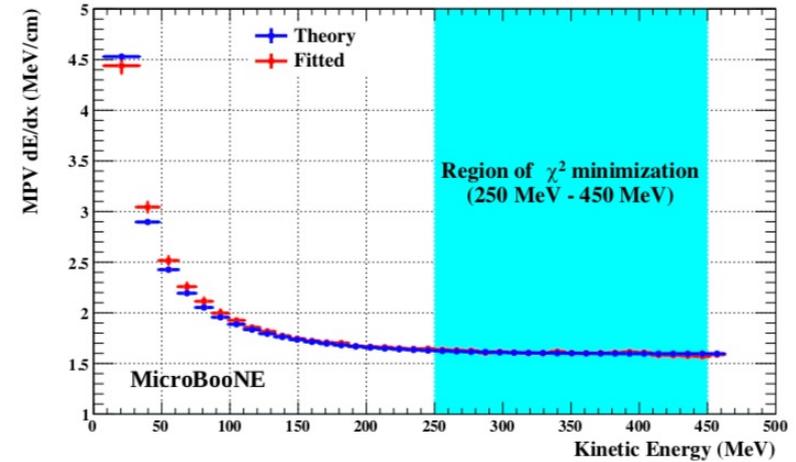
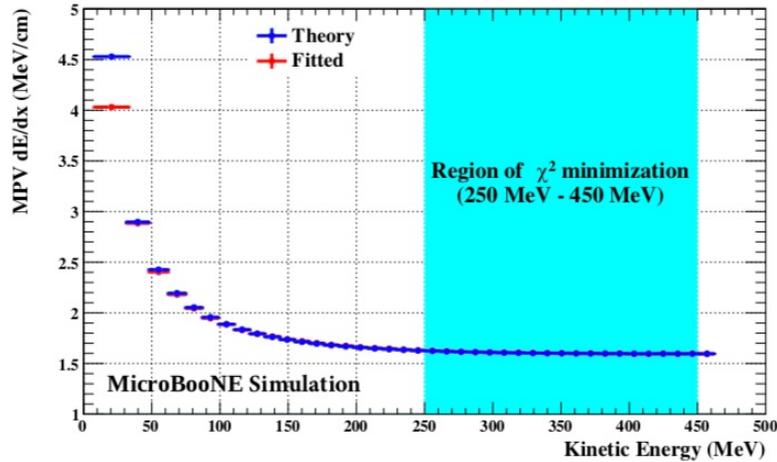
- C : Calibration constant to convert ADC values to number of electrons
 - W_{ion} : 23.6×10^{-6} MeV/electron (work function of argon)
 - ξ : 0.273 kV/cm (MicroBooNE drift electric field)
 - ρ : 0.212 (kV/cm)(g/cm²)/MeV
 - α : 0.93
- } ArgoNeuT: JINST 8, P08005 (2013)

$$\chi^2 = \Sigma\left(\frac{(MPV(dE/dx)_{prediction} - MPV(dE/dx)_{Measured})^2}{\sigma^2}\right)$$

Energy Scale Determination—dE/dx

- Once we find the calibration constants, we would expect the calibrated dE/dx matches expectation.

[JINST 15 P03022 \(2020\)](#)



- Kinetic Energy (K.E.) = $\sum \frac{dE}{dx} dx$, where dx is the track pitch.